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Effect of Recycling on the Material Properties of Three-Dimension Printer Filament

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MEMS 400 Independent Study

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Abstract

3D printing using Fused Deposition Modeling (FDM) has become a common tool for rapid and inexpensive prototyping in engineering. However, the process can be wasteful due to the unavailability of easy recycling options for failed and no longer needed prints. This study explores the effect on material properties of recycling printed plastic parts back into filament using Polylactic Acid (PLA) as the test material. This study establishes the recycling process and then uses it to attempt to recycle previously printed PLA parts into printable 3D printing filament. To implement the process, a plastic shredding device is built using inspiration from online sources, and commercially available Filastruder and Filawinder machines are assembled and calibrated for filament extrusion and winding. In combination with a Printrbot 3D printer, an attempt is made to print, shred, extrude, and then spool PLA filament. An Instron Universal Testing Machine and Bluehill 3 software are used to test material properties at each iteration of the recycling process utilizing both a tensile and a flexure test.

Introduction to Topic/ Significance

3D printing is currently driving the maker revolution within the United States. The industry has grown significantly over the last several years since patents have expired allowing startups and large corporations alike to introduction their own technology into the market. By 2020, the industry is forecasted to exceed $17.2 billion [1]. Because of this growth, it is important to study the technologies encompassing the field. Within the field, Fused Deposition Modeling (FDM) is a widely used process where filament is heated up to its melting point, fed through an extruder nozzle, and layered onto a build plate. Most FDM printers can use different types of plastics as material for the construction of objects. Because many 3D printed objects are used as prototypes or for the novelty of printing something physical that was created through Computer-Aided Design, many of the parts have a relatively short lifetime and are either thrown away or put away without further functionality. Additionally, because the field is new, 3D printers sometimes fail and parts are misprinted. These misprinted parts are almost always thrown away.

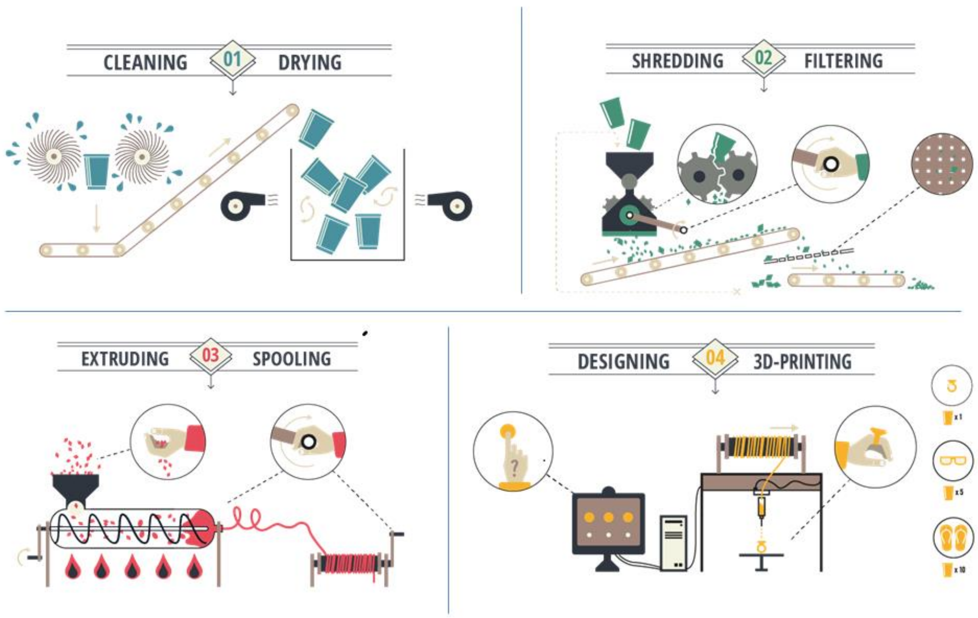
Over the last few years, multiple RepRap projects have centered around designing a process that can take printed parts and recycle them into new filament. Additionally, it may be (is? -reference?) possible to recycle plastic from everyday goods, such as plastic water bottles and milk jugs, into 3D printable filament. For the purposes of this study, this process will be called plastic and filament recycling. The process works through multiple steps (Figure (1) – Filament Recycling Diagram [4]):

1. The plastic (either from printed parts or everyday objects) is cleaned and dried.
2. Once dry, the material is shredded into pellets of a specific target size.
3. The pellets are heated to (the specific plastic's) melting temperature. Once heated, the plastic softens and is pushed through a nozzle at a specific diameter. As it exits the

nozzle, the plastic cools and forms filament. The filament is wound onto a spool (that is mountable onto a 3D printer).

4. The recycled filament is used for FDM printing.

Figure (1) – Filament Recycling Diagram [4]



Plastic and filament recycling thus presents a potential solution to addressing most of the plastic waste currently generated by 3D printers. Because the process is new, there is a lack of evidence to suggest how the material properties of the filament change throughout this recycling process. This is important to know when determining if this process is sustainable through multiple iterations. Even if the material properties do change, knowing the magnitude of the changes could help drive decisions on how to mitigate these changes in the future. If these changes were small, an additive (virgin resin pellets?) could potentially be added to the filament as it was recycled to help keep the changes to a minimum. The purposes of this study are to implement this recycling process here at Washington University in St. Louis and to try using it to recycle PLA plastic through multiple iterations to track material property changes through each iteration.

Material Properties

All solid materials have quantifiable properties such as strength, stiffness, ductility, coefficient of thermal expansion, glass transition temperature and other characteristics that may be measured to compare them to other materials and to test for consistency. There are many ways to test material properties, and two of the most common types of ways are to run tests called Tensile Tests and Flexure (also known as Three-Point Bending) Tests. To properly calculate the material properties of samples, these tests require dimensions for cross-sectional area (tensile test) and area moment of inertia (flexure test). The tensile test, possibly the most fundamental type of mechanical test, is relatively straight-forward. A sample is pulled and an isometric force transducer measures the force vs displacement curve. Properties that can be derived from this test are the modulus of elasticity (also called the Young's modulus), the yield strength, and the ultimate tensile strength [12]. Meanwhile the flexure test measures how materials behave when subjected to beam loading. The maximum fiber stress and strain can be calculated based on loading. To run the flexure test, a specimen is loaded between two supports and a load is applied to the middle of the specimen.

Hygroscopicity of PLA

PLA (Polyactic acid) is the main plastic used in this study. It is a polymer, meaning that it is a material made up of multiple repeating monomers. When these monomers are joined together, they form polymer chains which can degrade and be broken down. It other words, they depolymerize. This can happen due to a phenomenon called Hydrolysis in which a water molecule breaks a polymer chain. The material properties are significantly affected by hydrolysis. When a material absorbs significant amount of water, it is considered hygroscopic. In 3D printing, extruding filament that has absorbed water creates many problems. This is because the water vaporizes, creating air bubbles, and voids in the filament. These voids break polymer chains, and significantly weaken polymer chains. PLA is a material that is hygroscopic and thus absorbs water from the air easily. The importance of this will be discussed in the conclusion [9].

Methodology

Necessary Steps to Recycle

To recycle 3D printed or additional plastic samples scraped from bottles multiple devices are needed to create new filament. As discussed above, the plastic must be dried, ground/shredded, extruded, and wound onto a filament spool. These steps are critical when making new filament. For the purposes of the independent study, and for the sake of funding, a plastic dryer/dehydrator was not acquired to properly remove humidity from the plastic. This proved detrimental to the project, and will be discussed further down in the project pivot. To grind and shred the plastic, a grinder was built. A sheet metal mitre tool was also found to be useful for breaking parts into pellets manually. A Filawinder and a Filastruder were ordered, assembled, and calibrated. These devices were used to extrude and wind filament onto a spool respectively.

Designing and Building the Shredder

The grinding/shredding mechanism is important for the filament recycling process because any filament extruder can only process particles of plastic at a certain maximum size. For the Filastruder specifically, these particle sizes were to be no bigger than 5mm on each side. Funding for the independent study was limited as expected. Even though an effective method of grinding and shredding the plastic is essential to the filament recycling process, it was necessary to build and design a device instead of buying one. This is because most effective devices that could be bought online range cost several hundred dollars and up.

For inspiration, a design found through the Instructables website was used [2]. This design depends on two coaxial hollow steel pipes that are used as a cutting mechanism. The inner diameter of the outer tube was to be just slightly smaller than the outer diameter of the inner tube, to allow for rotation while preventing plastic particles from getting caught between the two tubes. The inner tube is rotated while the outer tube is fixed in place. This design was adjusted to allow for variability in the slot sizes. This design can be seen within the CAD drawing section below (Figure (5) - Grinder: Outer Tube).

To build the design, 1-foot long steel tubes were ordered from McMaster-Carr. The tubes were low carbon tubes where the outer tube had an inner diameter of 1 inch and the inner tube had an outer diameter of 1 inch. The line number for the inner tube was 7767T371 and the line number for the outer tube was 7767T65 (Figure (19) – McMaster-Carr Order). The tubes were cut and sanded with the help of Ivan Valkov [6] (Figure (4) Grinder: Inner Tube & Figure (5) - Grinder: Outer Tube). Once finished, a base was built to properly hold the shredder at any angle. This allows for shredded plastic to slide down the inner tube to be collected into a container. Additionally, a hole was drilled into the inner tube and a rod of that diameter was fitted through to allow a user to apply torque and turn the inner tube (effectively cutting the plastic). This rod and hole diameter is non-critical, if the rod is thick enough to withstand the torque applied to it through using the machine.

Filastruder and Filawinder Assembly and Calibration

To accomplish step 3 in the filament recycling diagram above, it was necessary to create a method to melt, extrude, and spool the created filament. There are multiple devices online, but the cheapest option (with good ratings to ensure effectiveness) came from the Filastruder website [8]. This option combines melting and extruding into one device called the Filastruder and executes the filament spooling process through a device called the Filawinder. It was decided that this was the more efficient approach to recycling plastic into new filament. Once the devices were bought and ordered, they needed to be assembled and calibrated. Assembly and calibration was based on the instructions given online. In addition to those instructions and the parts that came with the orders:

1. Wire nuts and additional wires were used to extend the wiring for the Filastruder.
2. The Thermocouple was attached with high-temperature glue from Home Depot. The Filastruder instructions recommended Kapton Tape but it did not work well when it was attempted.
3. While the horizontal hopper was used during horizontal Filastruder operation, a liquid funnel was also used to accurately guide plastic parts into the hopper.
4. Additional nylon-insert lock nuts were bought and Loctite Threadlocker Glue was used on many of the nuts on the Filawinder to prevent malfunction due to vibration of the Filawinder.
5. The Filastruder was mounted on an angle (more on that below).
6. The Filastruder fan was not used during ABS pre-testing. It was mounted for PLA recycling.
7. A new hopper was designed for use on the Filastruder while putting in plastic particles (more on that below).

To calibrate the Filastruder and Filawinder, a bag of ABS pellets came with the order. This bag allowed for multiple hours of use for both machines. For the Filastruder, the running the ABS pellets helped flush out bits of metal and other materials that were in the barrel so that there were no contaminants once filament recycling with shredded PLA pellets began. Additionally, as the ABS was extruded, the Filawinder was used to spool the resulting filament. This helped detect problems with vibrations and showed the need for threadlocking mechanisms for the nuts of the Filawinder. All tutorials used to calibrate the two devices are found through the Filastruder website [8].

Tensile and Flexure Tests

The tests run in this study were flexure (also known as 3-Point Bending) and tensile tests. This decision was made under the recommendation of Professor Ruth Okamoto [7]. The machine used was an Instron 5583 Universal Testing Machine (Figure (2) – Instron Universal Testing Machine) in combination with the Bluehill 3 software.

Figure (2) – Instron Universal Testing Machine

http://www.instron.us/-/media/images/instron/campaigns/legacy/4400.jpg?h=567&w=800&hash=9B80F68138918E5095BD5D51A3752735D8A2FFC9&la=en-us

To run the flexure test, the steps were as follows:

1. Take off the current load cell and unplug it from the load control.
2. Take out correct load cell (5kN) and secure load cell with screws.
3. Start-up Bluehill 3 software and establish communication with the Instron Machine.
4. Set machine into High Clutch setting and look for correct testing method through software (Flexure test).
5. Save test into correct folder and enter required quantities into software (rate = 10mm/min, support span).
6. Jog up to raise Instron, insert compression platens, and mount three-point bending apparatus.
7. Mount sample onto bending apparatus with the shiny (side touching print bed during printing) up. Move Instron level down to apparatus.
8. Balance the load and zero the extension in the software.
9. Click test and click start.
10. Once the sample has broken, click stop, hit return, and mount new sample.
11. Once finished, click finish and save work.

To run the tensile test, the procedural steps were:

1. Take off the current load cell and unplug it from the load control.
2. Take out correct load cell (5kN) and secure load cell with screws.
3. Dismount compression platens and mount wedge grips (labeled set 1 with top grip and bottom grip).
4. Start-up Bluehill 3 software and establish communication with the Instron Machine.

5. Set machine into High Clutch setting and look for correct testing method through software (Tension test).
6. Enter sample dimensions and load sample onto wedge grips.
7. Enter test controls (10mm/min with 240mm for end test) under method.
8. Go back to test menu. Balance the load and zero the extension.
9. Start test.
10. Once sample is broken, click stop.
11. Return grips to position. Dismount sample and load new sample.
12. Once finished, click finish and save work.

In addition to running the tests, samples needed to be designed. In working with Professor Ruth Okamoto, Professor Shaun Sellers, Professor Louis Woodhams, and Professor Ledjan Qato, samples for the tensile and flexure tests were designed. Individual tensile test samples were designed by Professor Woodhams (while working with Professor Sellers) and Professor Qato through Solidworks software. Then, the Cura software sliced the CAD designs, the Octoprint software to communicated with the 3D printers, and the Printrbots in Professor Woodhams's printed several samples of both CAD files. Even though both designs had similar cross-sectional areas, the samples printed via Professor Qato's designs more often broke down the middle as intended. Thus, his design was used while testing the material properties of the PLA. After training with the Instron machine, a 5-inch long sample was created using Inventor Pro software in consultation with Professor Ruth Okamoto. The sample drawings are shown in Appendix 1 on this report. In addition, printer settings were set to 100% infill, with 60˚ Celsius printer bed temperature, and 235˚ Celsius extruder head temperature when printing all samples.

Study Pivot

After the first set of printed PLA tensile and flexure test samples were run, they were ground up using the shredder and the metal mitre tool (mentioned below under Miscellaneous Additions). The resulting particles were through fed through the Filastruder. This proved to be ineffective as the produced filament had many problems. These problems were unsurmountable with the available time and budget of the study (discussed further in results and conclusion). Because of this, the goal of the study shifted from testing material properties of printed PLA samples at different iterations of the filament recycling process to testing factors that affected Filastruder PLA filament quality and documenting the results.

Designing Angle, Adjusting the Fan, and Gathering Results

As the study goals pivoted, angle and fan adjustments were made to ensure an optimal printing environment. In addition, filament was recycled at a range of temperatures to dial in a smaller range for more precise testing. The procedure for adjustment and dialing into a temperature range is below:

1. Mount the secondary fan onto the end of the Filastruder nozzle using blue tape. Keep the outer fan diameter 2mm from the nozzle tip to prevent the force of the air flow from altering the filament flow.
2. Design, CAD, and Print an angle [63.43˚ (2/1 tangent ratio)] to use for mounting the Filastruder using Inventor Pro and the Printrbot printers [Figure (18) – Mounting Angle].
3. Design and build a wooden mount for the Filastruder [Figure (16) – Filastruder Front ViewPlace the Filastruder into the mount to prevent slippage once it is vertically placed.
4. Attach the wooden mount with string to a counter-weight to balance the Filastruder. This will successfully help the Filastruder stay at an angle.

5. Test Filastruder with PLA particles from 190˚C to 170˚C at 5˚ increments while taking notes. This will help dial in on a temperature range which is most conducive to printing.
6. Once the temperature range is dialed in, produce filament at smaller increments of temperature change. Record observations on diameter consistency, how brittle the filament is, and take data on filament diameter in ten different places of produced filament using calipers.

Miscellaneous Additions to Project

Multiple items were added or improved to improve process flow. These items were adding a filament guide, adding a laser guide holder, adopting a metal mitre tool to shred particles, and redesigning the top hopper for future use.

Filament Guide and Laser Guide Holder

The Filawinder includes a novel laser guide to determine when the spooling mechanism should be activated. When calibrating, the laser shines a red vertical line onto a background, the user waves a piece of filament along the background, and the laser stores readings on the resulting shadow to determine at what level incoming filament is at. If incoming filament is below halfway on the vertical line, this indicates that there is some slack in the filament coming out of the Filastruder. The laser signals the controller and the spooling mechanism begins to operate, thus spooling filament onto the spool.

Video tutorials through the Filastruder website recommended mounting the Filawinder vertical onto a wall. A similar approach was taken as the Filawinder was mounted onto a piece of plywood to allow for it to be moved from place to place. The laser guide exists separate from the Filawinder as it needs to be positioned below the Filawinder. To attach the laser guide to the plywood, a laser guide holder was designed in Inventor Pro and printed through the Printrbot printer. Additionally, a small PLA filament guide was created to help guide the filament along a more even path between the laser guide and the main body of the Filawinder. This resulted in better process flow and mitigated errors that were occurring due to slack in the filament by accurately ensuring that all filament passed through the laser guide. Both the laser guide holder and the filament guide can be seen with the Filawinder in Figure (12) – Filawinder Front View.

Metal Mitre Tool

The proof of concept for the shredder cut well through bigger pieces of plastic, but this proved time inefficient when cutting pieces smaller than 20 mm. For the sake of time, a metal mitre tool was used to hand cut plastic pieces to the desired sizes of <5 mm. This tool is historically used to cove cap metal corners [3].

Redesigning Top Hopper

The Filastruder extrusion was converted from a horizontal to a vertical process so that gravity would not cause extruded filament to come out and directly touch the lower part of the nozzle. As the filament touched the nozzle, it would melt and clump due to the nozzle's temperature. Converting the orientation successfully caused extruded filament to come out perpendicularly to the nozzle. As the Filastruder extrusion was converted, the established funnel/hopper system proved inefficient. This is because the opening of the hopper was perpendicular to the barrel of the Filastruder. As the horizontal barrel was mounted vertically, the opening of the hopper became horizontal and plastic particles could not be kept in place. To alleviate this problem, a new top portion of the hopper was designed which could fit with the bottom half of the recommended hopper from the Filastruder documentation. This top hopper was not thoroughly tested during the semester but allows for use of the Filastruder in the future.

Results

PLA is difficult to recycle into usable 3D printing filament. After a majority of the semester was spent training, assembling, calibrating, and pre-testing the equipment used with ABS pellets, the necessary conditions were there for trials in recycled PLA. When the PLA was extruded through the nozzle of Filastruder, it came out brittle and the diameter was inconsistent. These observations led to predict that a problem arose with a material characteristic that we were not testing for: hygroscopic ability. This will be discussed in the conclusion, and what its implications are for the future. The implication to the results of this study were that PLA's hygroscopic ability prevented its recycling. Printable filament was not producible with the PLA particles that we had.

The purpose study dramatically shifted from testing material properties of PLA through multiple iterations of the printing, shredding, and recycling process to a focus on how to create the best conditions for filament recycling in the future. As discussed in the procedure, this shift meant that the study began dialing into the differences between ABS, which had been successfully extruded into filament, and PLA, which had proved problematic, and how better conditions could be pursued for recycling PLA in the future. These conditions were associated with a fan/no fan setting at the end of the nozzle, Filastruder orientation/angle, and a viable temperature range for creating consistent PLA filament.

The first two conditions were altered based on observation. With the Filastruder positioned horizontally, when filament would come out of the nozzle, it would directly stick to the bottom of the nozzle and clump up. This proved detrimental as the purpose was to create a steady flow of filament. To adjust for this initially, the Filastruder was manually held at an angle while conducting further trials for fan settings. With the Filastruder manually held at an angle, and no fan at the end of the nozzle, regardless of the temperature, the PLA would fall apart under its own weight right as it came out the nozzle. To adjust for this, the secondary fan was mounted using blue tape (with the outer diameter 2mm away from the nozzle hole) to help the outcoming filament cool faster allowing for it to retain shape as it came out. After the fan was mounted, the Filastruder was secured onto the angled mount (at 63.43˚) to ensure for a consistent angle. This allowed for attention to be diverted from holding the Filastruder up manually to more closely observing the flow of filament from the nozzle.

After the Filastruder fan was added, but before the machine was mounted on an angle, preliminary testing trials to dial into an appropriate temperature range were run. The observations for these trials are shown in the table below in Table Table (1) – Initial Filament Temperature Table with Observations.

Table (1) – Initial Filament Temperature Table with Observations

Temperature (Celsius)	Observations
190	Produces very thin filament. It is inconsistent in diameter, and comes out relatively think, but is soon stretched out by its own weight. In addition, it is very brittle
185	Produces very thin filament. It is more uniform in diameter than 190 C, but it requires more looking after. It becomes wavy often, so it must be hand pulled to be separated.
180	Still brittle, clumps up even easier that 185 C. But once steady flow is going, it is relatively a consistent diameter. Additionally, it curves easily while cooling

175	Filament is noticeably thicker. It has the most consistent flow from any filament temperature thus far. Additionally, it has white streaks along it, perhaps indicating that it's too cold. It did need guidance at first but it corrected itself.
170	White streaks were again present. Filament diameter was initially thicker than any other temperatures, but began to fall apart under its own weight. Thus, filament diameter was largely inconsistent.

From this table, we can conclude that the higher the temperature, the thinner the filament produced. While the filament lacked consistency throughout, this preliminary trial served as a good guide to spot the relation between filament diameter and nozzle temperature. It is also important to keep in mind that this was before the Filastruder was mounted, as the filament diameter proved inconsistent at almost all temperatures (besides 180˚ C).

Once the Filastruder was mounted on the 63.43˚ angle, the system had a consistent set of test variables besides temperature. Thus, resulting changes in filament diameter could be linked directly to changes in filament. Initially, a test was run at 165˚ C. The average diameter for this test was 2.17 mm but diameter fluctuated widely from 2.04 mm to 2.43 mm. The second test, at 170˚ C, delivered an unexpected result. While the diameter was supposed to decrease, it decreased dramatically to an average 1.59 mm. To the human eye, it appeared to be more consistent. Because standard filament has a nominal diameter of 1.75 mm, it was established that the desired temperature needed to be dialed in somewhere between 165˚and 170˚. After several trials between 165˚C and 170˚ C, the closest average values to 1.75 mm were 1.82 mm and 1.68

mm at 167.5˚C and 167.0˚C respectively. But, this result is the opposite of the general trend that warmer temperatures create thinner filament.

In addition, the discussed trials above were conducted when the barrel was partially full of recycled filament. Two trials were run with the barrel completely full. These trials, at 165.0˚C and 160.0˚C, produced thinner filament than trials where the barrel was partially full. They produced average filament diameter of 1.47 mm and 1.59 mm respectively, adhering to the general trend between temperature and filament diameter. The results for all trails are given separately in Appendix 3 and are shown together in Figure (3) – Average Filament Diameter vs. Set Thermocouple Temperature and Table (2) – Average Filament Diameter vs. Temperature below.

Table (2) – Average Filament Diameter vs. Temperature

Temperature (Celsius)	Average Filament Diameter (mm)	How full was the barrel?
165.0	2.17	Semi
170.0	1.59	Semi
167.5	1.82	Semi
168.5	1.65	Semi
168.5	1.57	Semi
168.0	1.59	Semi
167.0	1.68	Semi
165.0	1.47	Full
160.0	1.59	Full

Table 3 and 4 below display the initial results for the Young's Modulus found by running a tensile test and a three-point bending test respectively. The average Young's Modulus for the tensile test was 1.19 GPA while it was 3.26 GPA for the three-point bending test. Interestingly, this is lower than the known value of 3.5 GPA [14]. While the three-point bending test was close to this number, the tensile test results were almost three times lower. This may be accredited to the print orientation and adhesion in the samples when printing the dogbone shapes for the tensile specimens.

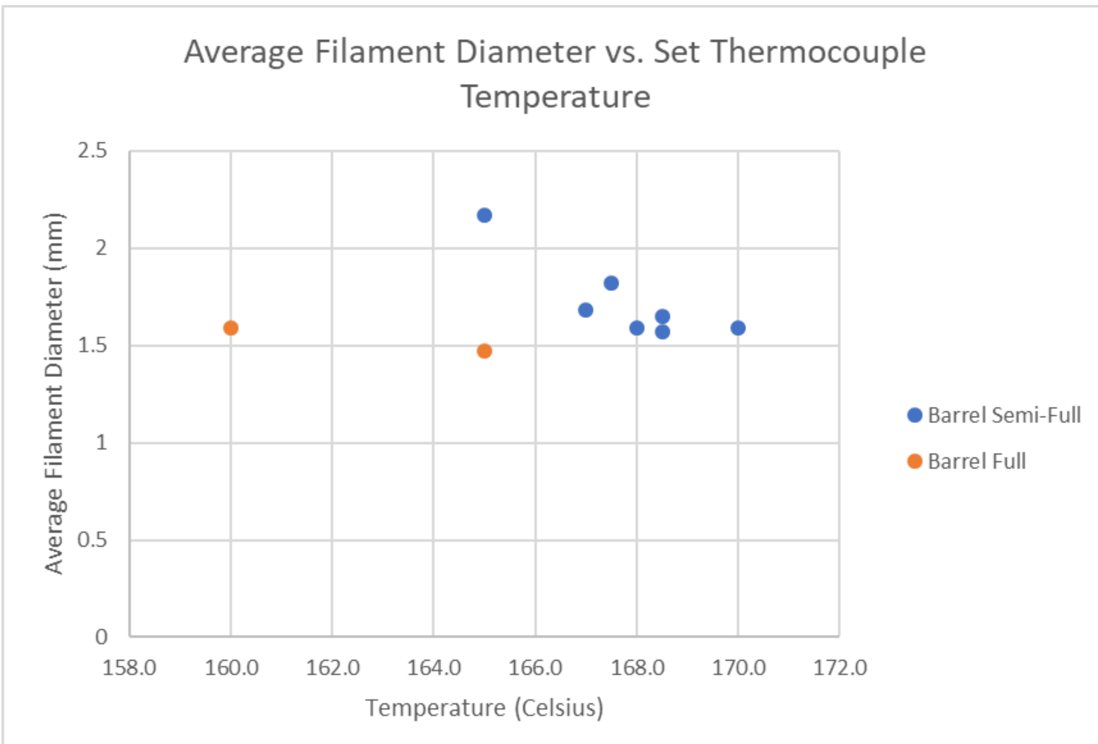
Table (3) – Test Results for Tensile Test During First Iteration

Young's Modulus Results Tensile Test	
Trial	Young's Modulus (GPA)
1	1.20
2	1.15
3	1.13
4	1.13
5	1.06
6	1.19
7	1.17
8	1.31
9	1.19
10	1.24
11	1.21
12	1.34
Average	1.19

Table (4) – Test Results for Three-Point Bending Test During First Iteration

Young's Modulus Results Three Point Bending Test	
Trial	Young's Modulus (GPA)
1	3.28
2	3.38
3	3.17
4	3.21
5	3.27
6	3.27
Average	3.26

Figure (3) – Average Filament Diameter vs. Set Thermocouple Temperature



Discussion/Conclusion

This study confirmed that producing filament is possible, but it requires careful consideration and observation. The comparison between PLA material properties at different iterations was not possible due to the hygroscopicity of the polymer. While there is no validation that the hygroscopicity of PLA was the problem, observations and discussion led to this prediction. The PLA filament produced was brittle. After contacting support at Filastruder and review from experienced sources, it is concluded that brittle PLA filament is caused by moisture in the PLA just before extrusion [8][9][10]. Yet, the factors are almost in place for this process to be standardized at the University going forward.

Effect of Hydrolysis

The hygroscopic property of PLA proved detrimental to the recycling ability of this study. While this was rather unfortunate, there are viable solutions. Steps can be taken to mitigate the amount of water absorbed by PLA and other plastics that are to be recycled in the future. One approach to drying shredded particles in to heat them in the oven. At around 160-180˚F (not Celsius), the particles should be left in the oven for 4-6 hours before extruding using the Filastruder. For best practices, the particles should be kept in low moisture areas before and after extruding to ensure best quality filament for printing [9].

Another approach is to use a food dehydrator. Other users of the Filastruder have successfully recycled 100% old PLA using a food dehydrator. After letting the pellets sit for 10-17 hours, they should be sealed to be kept dry. An additional way to ensure better filament is to mix virgin pellets with shredded plastic particles. The virgin pellets will come dry and lock tight which will ensure that they have a lower level of water inside of them [10].

Discussion on Final Results

To continue using this process, a drying mechanism to counteract against hydrolysis will be necessary. While the final results are not conclusive, because drying the particles may completely change at what temperatures filament can be consistently extruded at, our results show trends that should not be overlooked. First and foremost, when analyzing the preliminary results, and the results of both the semi and fully filled barrel, it can be concluded that the higher the temperature, the thinner the filament that will be extruded. Additionally, by comparing the semi-filled barrel results to the fully-filled barrel results, it can be concluded that a fully-filled barrel extrudes thinner filament. This is most likely due to their being a larger force on the filament within the end of the barrel just before it is pushed out of the nozzle. With a larger force, the filament will flow faster out of the nozzle and will then be thinner.

Difficulties Experienced and Future Recommendations

The most time-consuming part of this process is the time and effort spent towards shredding the plastic. While the shredder built in this project served as a good proof of concept and managed to shred plastic effectively, it would be an inefficient use of time for someone to use the shredder manually to grind through a substantial quantity of plastic. If the filament recycling process is continued at the University, it would be wise to buy or build an automatic shredder that significantly reduces the manpower necessary for grinding the particles. If the designed shredder were to be used, a half cylinder should be designed to the inner diameter of the inner tube. This is because the diameter of the inner tube is too large for smaller particles to be shredded effectively through it at current state. Currently, smaller particles just fall through the holes present. With a half cylinder, this would decrease the volume in the inner tube, allowing for more thorough shredding. In addition, a funnel should be designed for the current shredder if it is used in the future, as it will help section particles to fall into the correct holes for effective grinding.

Additional upgrades to the system will be to place the device in a well-ventilated area with proper airflow and low humidity. While PLA is non-toxic, produced PLA filament did have a terrible smell to it. If the process is to be used for toxic plastics that could be used as 3D printing filament, this step will be necessary to reduce the potential harm to humans. A low humidity area will help prevent hydrolysis in the plastic polymers that this process has the potential to recycle.

If the recommendations are taken forward, and the process is upgraded, the possibilities are limitless. Filament recycling has opened new doors for recycling. People have successfully recycled red solo cups into usable filament (contrary to popular belief, red solo cups cannot be recycled) [5]. This process has the potential to save the University a lot of money. Filament prices online range from $15 to $50 per kg. A study shown in the Journal of Cleaner Production showed a team producing a kilogram of recycled filament for about 10 cents. This cost savings potential is drastic. Furthermore, the energy demand for producing this plastic was 10.97% to that of producing virgin plastic by the kilo and was about 3% more energy efficient than centralized recycling. Lastly the greenhouse gas emission of this process was 17.4% less than that of centralized recycling [11]. These figures speak for themselves.

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I would like to thank these people for their contribution to this project. Without their support and advice, this amount of work cannot have been accomplished within the timeframe:

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Appendices

Appendix 1: CAD Models

Figure (4) Grinder: Inner Tube

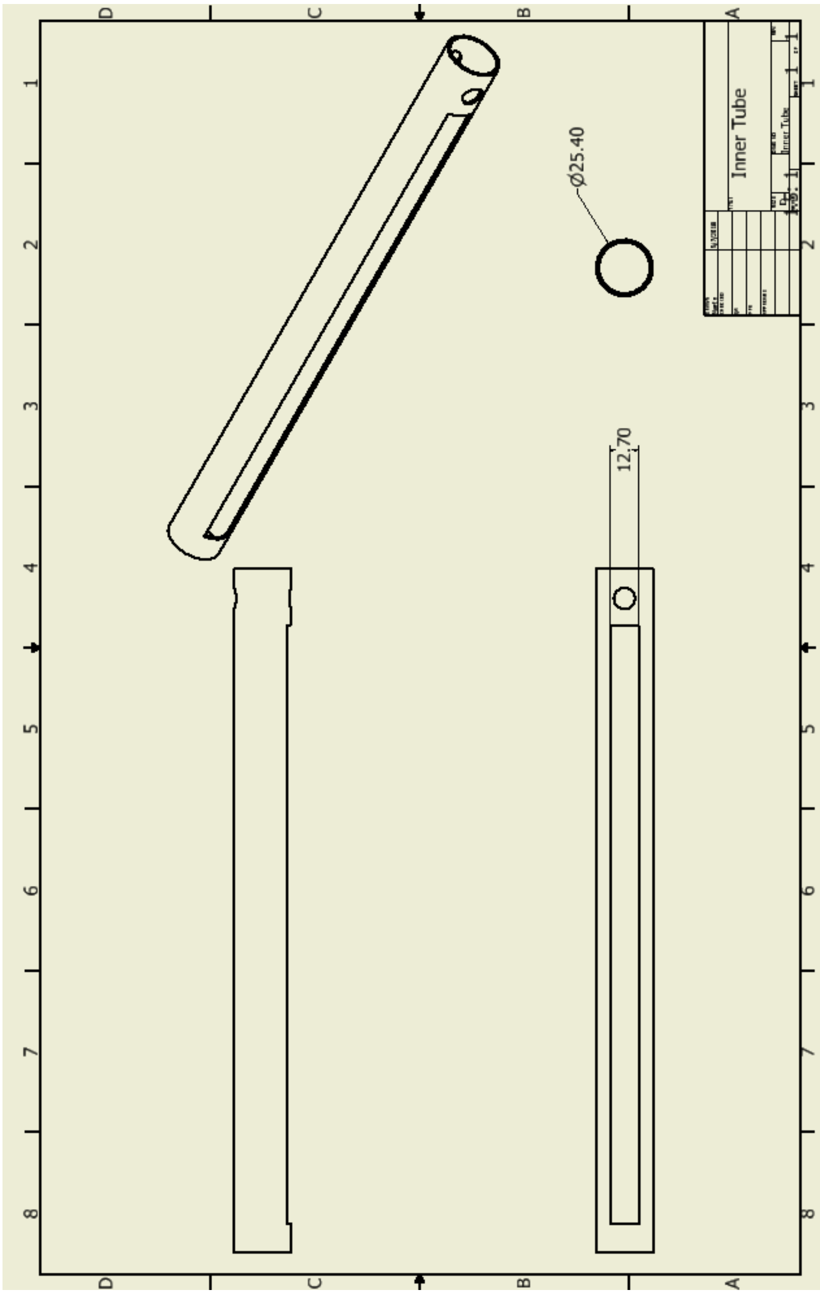


Figure (5) - Grinder: Outer Tube

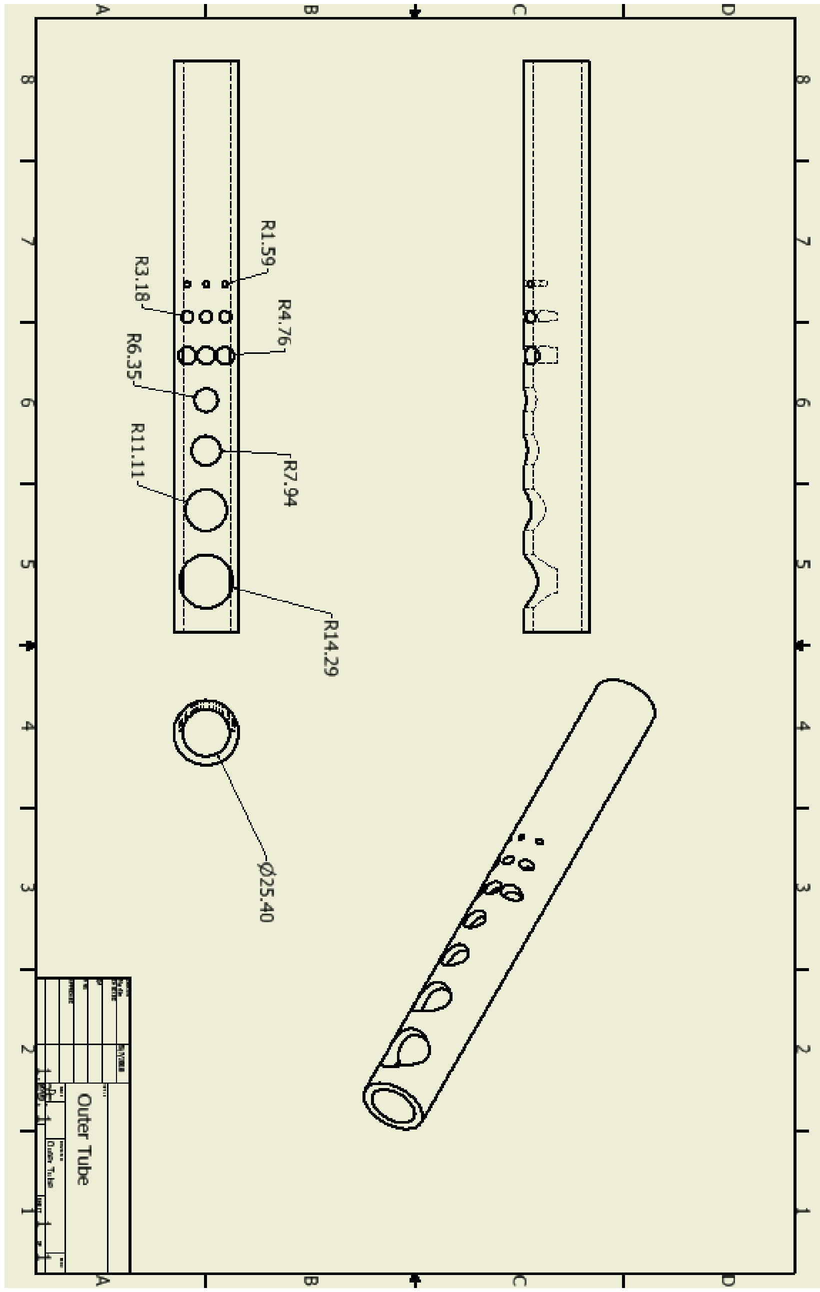


Figure (6) – Grinder: Assembly

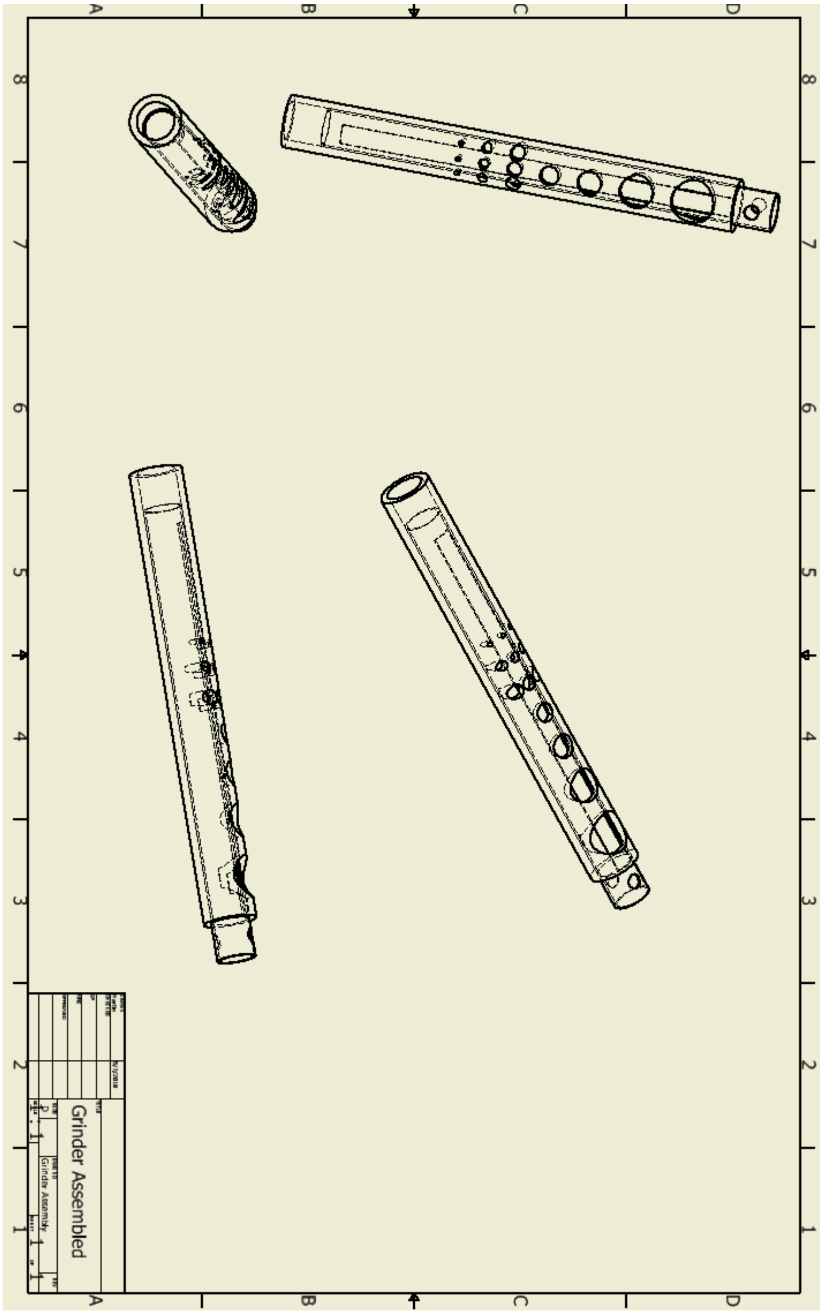


Figure (7) – Three Point Bending Sample

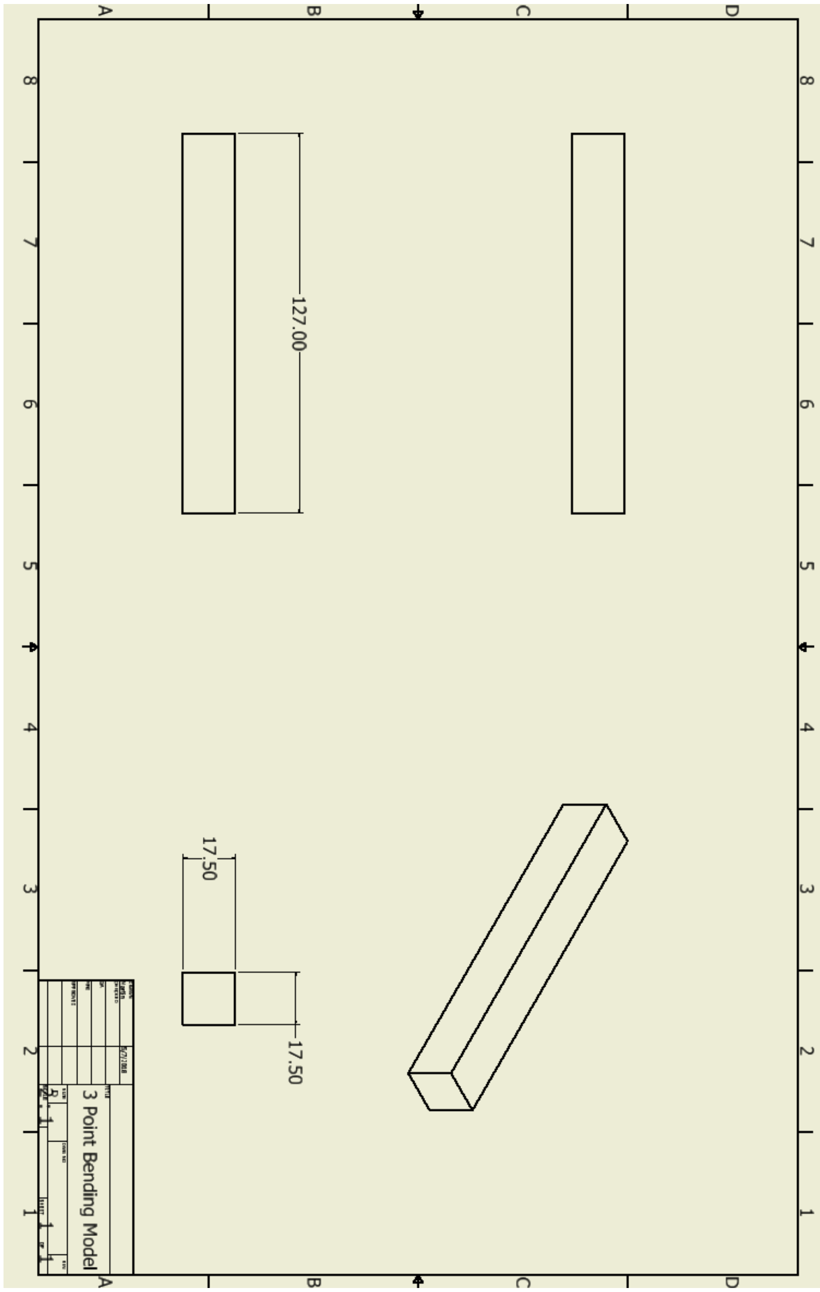
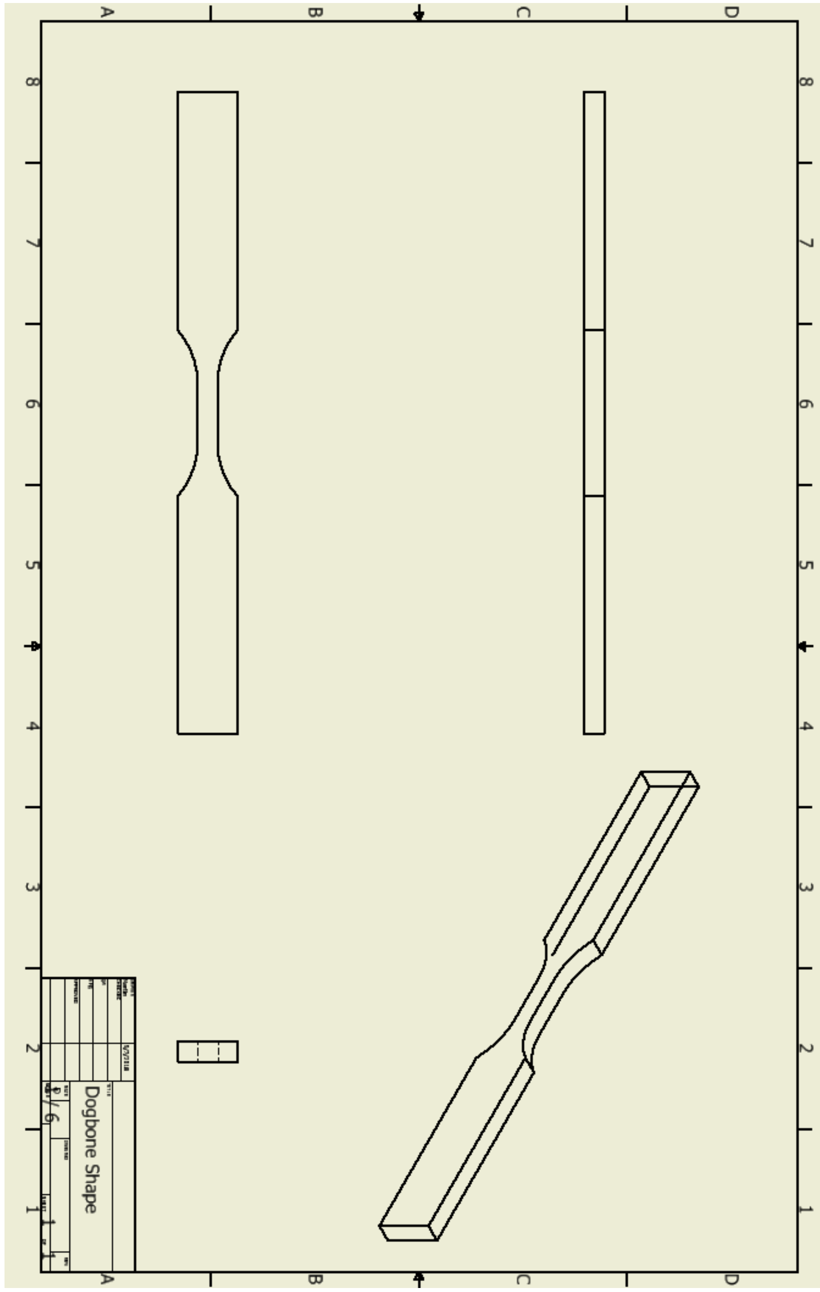


Figure (8) – Dogbone Shape Sample



(note: dimensions are not included due to availability of file only in STL format. Thus, dimensions did not convert correctly. During experiment, size for crosshead area was 3.61 mm (w) by 3.34 mm (t). Length of thin straight on Dogbone was 15.45 mm.)

Appendix 2: Pictures

Figure (9) – Shredder Top View

Figure (10) – Shredder Isometric View

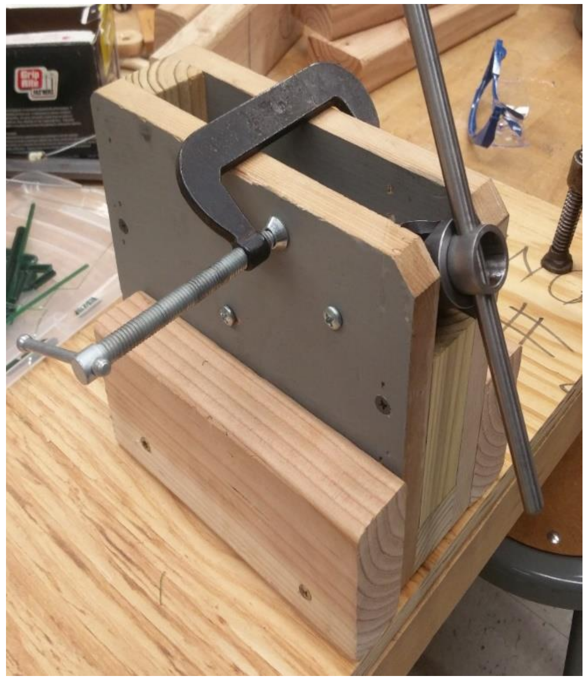


Figure (11) – Shredder Side View

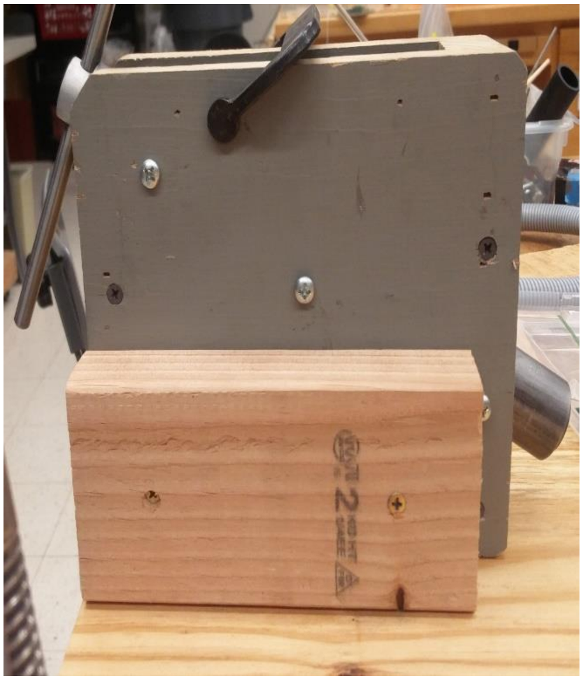


Figure (12) – Filawinder Front View

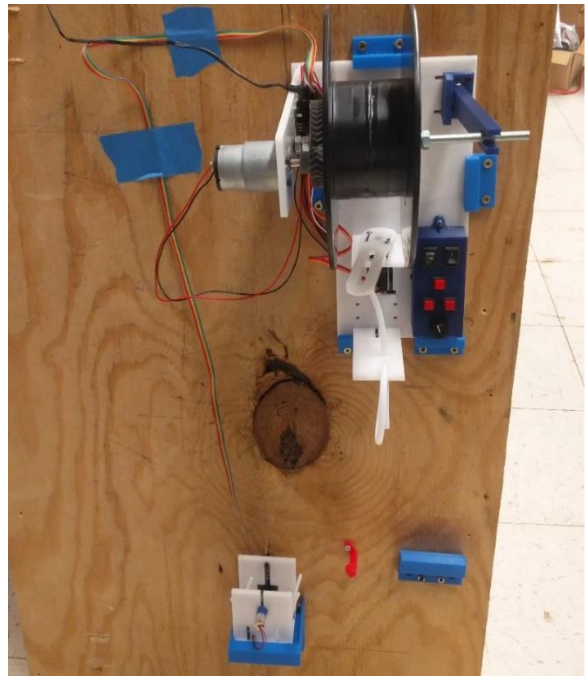


Figure (13) – Filawinder Side View

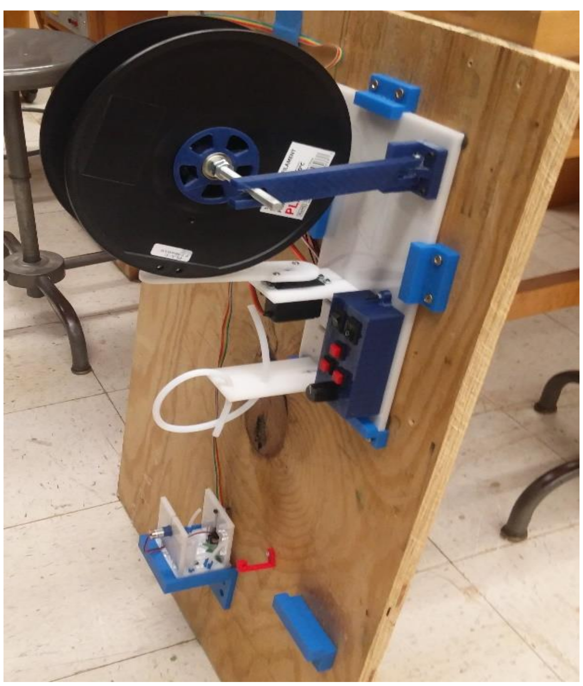


Figure (14) – New Top Half Hopper Side

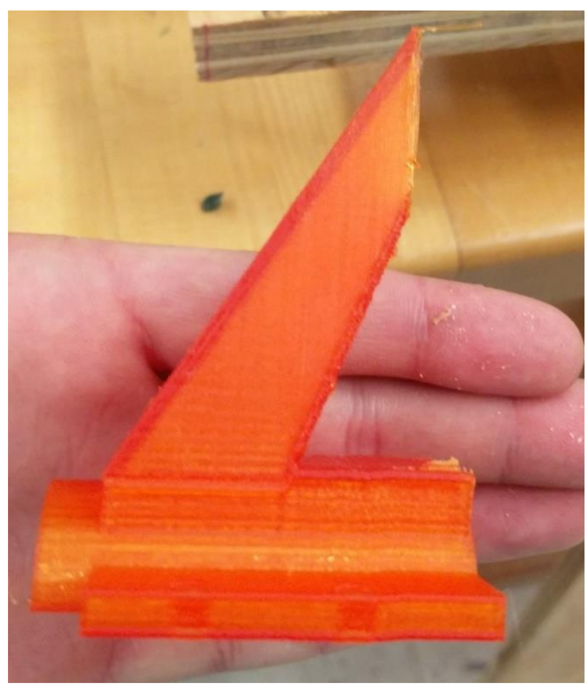


Figure (15) – New Top Half Hopper Front

Figure (16) – Filastruder Front View

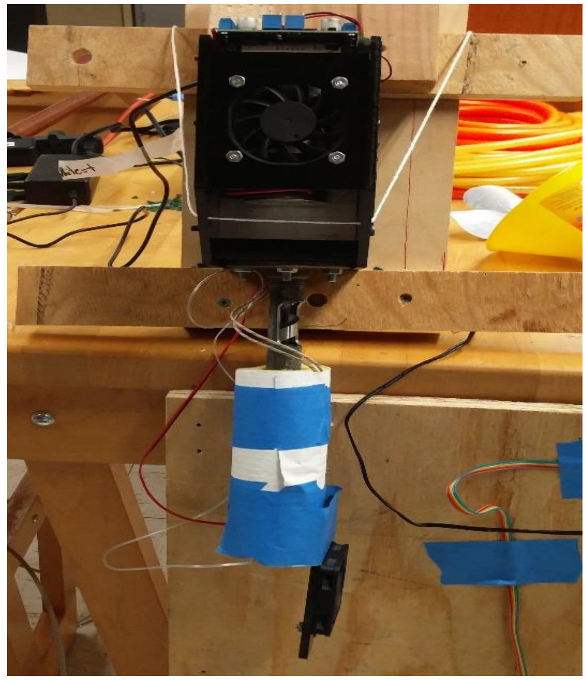


Figure (17) – Filastruder Side View

Figure (18) – Mounting Angle

Figure (19) – McMaster-Carr Order

Martin Valkov placed this order.

Line		Product	Ordered	Shipped	Balance	Price	Total
1	7767T371	Low-Carbon Steel Round Tube, 0.120" Wall Thickness, 1" OD, 1 Foot Long	1 Each	1	0	5.07 Each	5.07
2	7767T65	Low-Carbon Steel Round Tube, 0.188" Wall Thickness, 1-3/8" OD, 1 Foot Long	1 Each	1	0	15.74 Each	15.74

Appendix 3: Results

Table (5) – Filament Diameter Measurements 165.0˚C (Trial 1)

Diameter (mm)	Temperature (Celsius – Trial 1)
2.15	165
2.04	Observations
2.43	It seems slightly less brittle than filament tested earlier today. Diameter is still inconsistent, but is thicker than any previous trials
2.17	
2.34	
2.16	
2.07	
2.27	
2.04	
2.04	
Average	
2.17	

Table (6) – Filament Diameter Measurements 170.0˚C

Diameter (mm)	Temperature (Celsius)
1.79	170
1.66	Observations
1.67	Filament diameter is even more consistent. It does slightly decrease as time passes. This is likely
1.56	
1.64	

1.34	because of gravity and the weight of the filament pulling on itself.
1.64	
1.67	
1.53	
1.44	
Average	
1.59	

Table (7) – Filament Diameter Measurements 167.5˚C

Diameter (mm)	Temperature (Celsius)
1.74	167.5
1.77	Observations
1.72	Diameter gets thicker the farther up the measurements go. Consistency is good. Seems less brittle. Diameter may change because I was trying to calibrate Filawinder simultaneously
1.73	
1.78	
1.81	
1.87	
1.94	
1.95	
1.9	
Average	
1.82	

Table (8) – Filament Diameter Measurements 168.5˚C (Trial 1)

Diameter (mm)	Temperature (Celsius – Trial 1)
1.68	168.5
1.8	Observations
1.66	Consistency is good. Slightly getting thinner under its own weights due to gravity.
1.68	
1.6	
1.64	
1.6	
1.75	
1.57	
1.5	
Average	
1.65	

Table (9) – Filament Diameter Measurements 168.5˚C (Trial 2)

Diameter (mm)	Temperature (Celsius – Trial 2)
1.7	168.5
1.58	Observations
1.55	Similar to trial 1 at 168.5. Consistency is good, got thinner due to its own weight.
1.45	
1.42	
1.39	

1.52	
1.64	
1.7	
1.73	
Average	
1.57	

Table (10) – Filament Diameter Measurements 168.0˚C

Diameter (mm)	Temperature (Celsius)
1.56	168
1.6	Observations
1.64	Consistency is good. Thinner as time went on due to effects of gravity
1.63	
1.5	
1.44	
1.69	
1.66	
1.62	
1.57	
Average	
1.59	

Table (11) – Filament Diameter Measurements 167.0˚C

Diameter (mm)	Temperature (Celsius)

1.68	167
1.69	Observations
1.73	Similar observations to 168 degrees Celsius
1.56	
1.66	
1.73	
1.65	
1.69	
1.7	
1.72	
Average	
1.68	

Table (12) – Filament Diameter Measurements 165.0˚C (Trial 2)

Diameter (mm)	Temperature (Celsius)
1.44	165 (Trial 2)
1.42	Observations
1.7	Thinner than other temperatures - not characteristic of trends observed. This is likely due to barrel being completely full during this trial, putting more force on extruding (thus extruding faster)
1.41	
1.40	
1.36	
1.42	
1.43	

1.52	
1.58	
Average	
1.47	

Table (13) – Filament Diameter Measurements 160.0˚C (Trial 2)

Diameter (mm)	Temperature (Celsius)
1.67	160
1.62	Observations
1.73	Similar results as second to last trial at 165 (thinner than higher temperatures which is against the trend). This is likely due to barrel being completely full during this trial, putting more force on extruding (thus extruding faster). But it is thicker than at 165.
1.57	
1.59	
1.54	
1.54	
1.49	
1.56	
1.58	
Average	
1.59	

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